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Investigation of Retrofit Solutions of Window-Wall Assembly Based on FMEA, Energy Performance and Indoor Environment

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ABSTRACT

Multi-storey buildings built before the 1960s have a large energy saving potential. The windows and facades are the two components with largest saving potentials. Many buildings from the period before 1960s have windows and facades worth to preserve from an architectural point of view and therefore outside insulation is not possible. Development of new retrofit solutions should be long-lasting and not cause collateral damage to the existing structures.
This paper describes a rational optimisation approach for analysing retrofit solutions based on durability, energy savings and indoor environment. The failure mode and effect analysis is used for assessing the durability. The energy saving is calculated as the heat loss through frame and joint. Daylight simulations are performed to evaluate the indoor environment. In the paper two window-wall assemblies are investigated, a window with a secondary glazing and a box window both with internal insulated walls.
The thermal result shows that a box window has the lowest heat loss and heat loss transmittance. The daylight for the two window-wall assemblies performs equally but worse than the existing window-wall assembly. The durability of the assemblies is most critical to moisture from the inside. The box window has the lowest temperatures on the surface and therefore more vulnerable toward condensation.
The basis of the rational optimisation approach is the total economy considering the initial, operational and maintenance costs over the buildings lifetime. The maintenance costs can be found from the durability assessment as the indoor environment and energy calculations covers the operational costs.

KEYWORDS

Window-wall assembly, FMEA, Energy savings, Retrofit optimisation

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1 INTRODUCTION

Retrofitting old multi-storey buildings built before the 1960s have a large energy saving potential and can contribute to meet the demand in EUs energy and greenhouse gas emission target for 2020 [EU 2008]. Windows and facades are the two components with the largest saving potential [Wittchen 2009]. Many of the buildings are with facades worth to preserve, hence only inside insulation is possible. In Denmark the 4-light "Dannebrog" windows have to be kept from an architectural point of view. Applying inside insulation increases the thermal bridge in the window-wall assembly. Inside insulation also takes up room space and herby decreases the daylight into the room. Retrofitting the windows combined with internal insulations on the walls leaves a thermal bridge in the window-wall assembly. This thermal bridge can be difficult to minimize without also reducing the window size. For low-energy buildings the thermal bridges greatly influences the total heat loss. The assembly between the window and wall will be analysed using Failure Mode and Effect Analysis (FMEA) with regards to durability, and will furthermore be analysed considering the energy saving potential and indoor environment.
Retrofitting old buildings it is important that no collateral damage to the existing structures are made. It is therefore necessary to develop new long-lasting retrofit solutions that have been tested thoroughly for failures. The use of quality improvement tools such as FMEA can be very valuable analysing the solutions. This paper presents a rational optimisation approach for analysing retrofit solutions based on durability, energy savings and indoor environment as retrofit solutions often only consider energy savings. In this paper a window with a secondary glazing and a box window are investigated.

1.1 FMEA and Window-Wall Assembly

Layzell and Ledbetter [1998] applied FMEA to cladding systems. The causes of failures where found from test failures and from experiences on site. The knowledge of causes helped determine a more precise risk priority number (RPN). In IEA-SHC Task 27 [Köhl 2007] solar collectors and windows were investigated using FMEA. The RPN was based on knowledge based data for occurrence.
Zhang et al. [2010] studied a fuzzy risk priority number based on method integrating weighted least square method. The method of imprecision and partial ranking method is proposed to generate more accurate fuzzy RPNs and ensure to be robust against the uncertainty. The fuzzy RPN are determined on a multidimensional scale spanning occurrence, severity and detection along with their different interaction under a fuzzy environment. The focus is on component level and not interaction between components.
The determination of the RPN can be done in several ways and can influence the durability of the structure greatly. Another approach could be Monte Carlo simulations.

Salzano et al. [2009] has identified the interaction between window and wall as a significant source to water intrusion trough the building envelope in high-humidity, hurricane-prone areas. The same problem occurs with high loads of driving rain. It was found that the water barrier method is preferable for windows integrated into masonry walls. The water barrier method means that the interior surface of the window's mounting flange receives a continuous bead of sealant to provide a moisture and air barrier at the external interface of the window opening. By retrofitting building envelope it is important to make sure that the interaction between window and wall are moisture tight.

FMEA has been applied on component level with many approaches to determine the RPN. The FMEA will be applied on the interaction between two components, where the RPN not will be determined. Unlike the previously work the FMEA will be used on an assembly instead of a component, because the challenge is to maintain the original window and wall without making any changes to the architecture. The window-wall assembly is interesting because the appearance of the window and wall should be preserved. Previously work has shown that a lot of moisture problems occur in this assembly and large energy savings can be achieved.

2 WINDOW-WALL ASSEMBLY

Figure 1 shows the principle structures in the window-wall assembly for the existing structure, a window with secondary glazing and a box window.

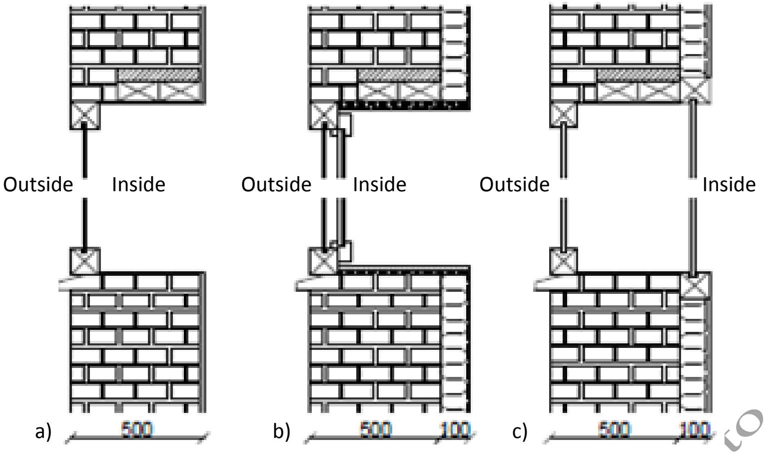


Figure 1. a) The existing structure with single glazed window. b) Solution 1 with the existing window and a new secondary window with a double energy glazing. c) Solution 2 with the existing window and a new window in the inside insulation.

The existing structure consists of a 0.5 m width brick wall, where the window with one layer glass is placed outside in the wall. Above the window wooden beams supports the brick wall. In both renovation solutions the outer wall is insulated with 100 mm internal insulation. In solution 1 a double glazed energy window is added as a secondary glazing on the inside of the existing window. Furthermore the thermal bridge in the window panel is insulated with 20 mm mineral wool, to minimize the heat loos. The frame for the second glazing is made of wood.

In solution 2 a double glazed energy window is added on the inside of the wall without any connection to the original window. The frame, which is made of Glass-reinforced plastic (GRP), is placed in the layer of insulation.

3 FAILURE MODE AND EFFECT ANALYSIS (FMEA)

FMEA was developed in the aerospace industry and has been adapted in many other lines of business. The FMEA method is a systematic and analytic quality planning tool for identifying effects of potential failures. In Fig. 2 the steps of the FMEA process are shown which also is described by Stamatis [2003] and McDermott *et al.* [2008].

The FMEA comprises three general steps.

1. Identification of potential failure modes, effects of failure modes and causes of failure modes.
2. Ranking (1-10) of causes of failure according to likelihood of occurrence, severity of the effects and (non)-detection of the failure. Multiplication of the three factors gives the risk priority number (RPN).
3. Problem follow-up and corrective actions for improvement to be taken on high RPN or severity x occurrence or severity.

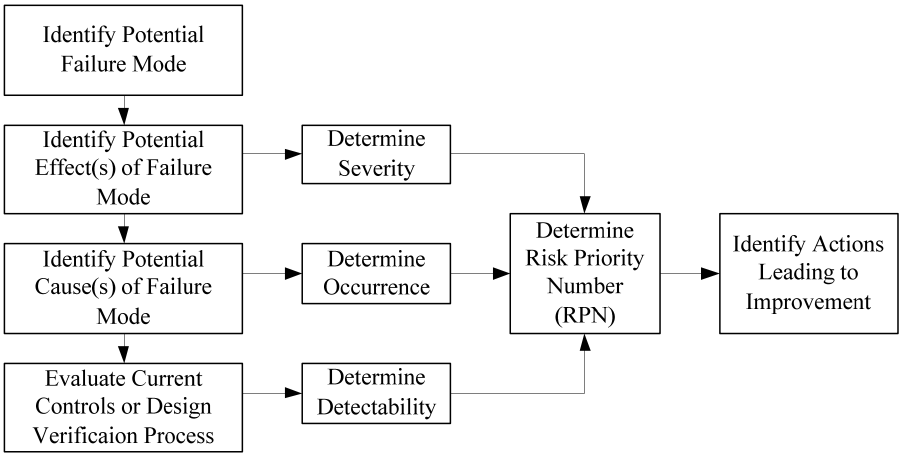


Figure 2. The process of Failure Mode and effect Analysis

3.1 FMEA on Window-Wall Assembly

The FMEA focuses on identifying potential failures which affects the durability of the retrofitted window-wall assembly. In Table 1 the failures for both retrofit solutions are shown combined with potential effects and causes. The effects of the potential failure are described in Table 2 based on rational assessments and referred to with numbers in Table 1.

Table 1. Potential failure mode, effects and causes for the two retrofit solutions.

Failure mode	*Effects* (Table 2)	*Causes*
1. The caulking joint is leaking. Water accumulates under the window panel.	6	The existing joint is probably old and cracked. Another explanation of the leaking could be that the joint is missing.
2. The weatherstrip between the existing casement and pane is leaking. Drying to the inside is reduced due to the new window.	4	The weatherstrip has lost the attachment because of aging or workmanship.
3. The weatherstrip between existing and new casement is leaking – This is only important if failure mode 2 also occur (only valid for solution with second glazing).	1, 2, 4, 5	The weatherstrip has lost the attachment or is missing.
4. Draughty assembly in the vapour barrier, which cause condensation in the structure.	6, 8	There have been penetrations of the vapour barrier while carrying out or afterwards.
5. The weatherstrip between casement and frame in the existing window is leaking. Drying to the inside is reduced due to the new window.	3, 4, 5	The weatherstrip is old and must be replaced or is missing. The weatherstrip is pushed instead of pressed when the window is closing.
6. Deformation of window hole, as a consequence of the inside insulation which affect the temperature profile in the wall.	7	Subsidence in the building because of the changed temperature in the wall by internal insulation.
7. The bearing construction decomposes (the wooden beam over the window) as a consequence of moisture accumulation.	9	The wall gets cold because of the internal insulation and reduced drying potential.
8. Moisture accumulation in the wall.	8	The drying potential is reduced because of the internal insulation.

9. Condensation in the cavity on inside of the outer window and wall (only valid for the box window).	3, 6	The temperature in the cavity is below dew-point when warm humid air entered the cavity through draughty weatherstrip.

Table 2. Potential effects by retrofitting window and wall.

Potential effects	
1. Condensation on the inner side of the outer pane	6. Decomposition of panel in the window (rot)
2. Increasing the heat loss	7. Failure in the tightening
3. Moisture in the cavity	8. Mould between wall and inside insulation
4. Decomposition of the casement (rot)	9. The wall is collapsing
5. Decomposition of the frame (rot)	

In the FMEA analysis most of the failures are the same if the solution with secondary glazing or a box window is chosen. It is clear that most of the failures are related to the weatherstrips different places in the construction; hence moisture is the most critical issue.

4 METHODS FOR SIMULATIONS

4.1 Geometry

In Fig. 1 the three window-wall assemblies are shown. In the thermal calculations the masonry wall was 0.5 m thick and 1 m high. On the inside of the wall 100 mm insulation with wooden skeleton was applied. The existing window frame was 83 x 128 mm (H x W) and the box window frame was 57 x 119 mm. The window height was 0.2 m and applied as 1 layer glazing, 1+2 with small (30 mm) and large air cavity (452 mm). As cold bridge insulation 20 mm mineral wool was applied in solution 1.

4.2 Boundary Conditions and Materials

The interior and exterior environment was described by boundary conditions for temperature and relative humidity. The inside air temperature was constant 20°C and the relative humidity 50%. The exterior climate was described by a constant outside air temperature of 0°C and a relative humidity of 80%.
The surface heat transfer resistance was 0.13 ($m^2\cdot K$)/W for internal surfaces with horizontal heat flow and for outside surfaces 0.04 ($m^2\cdot K$)/W according to [EN ISO 6946:2007]. For the box window the resistance of the air cavity was calculated and distributed to the cavity surfaces with half (0.10 ($m^2\cdot K$)/W) of the total cavity resistance (0.19 ($m^2\cdot K$)/W).

The thermal calculations were performed with the material properties listed in Table 3 taken from [DS 418:2002].

Table 3. Material properties for thermal calculations.

Material	*Thermal conductivity, λ* [W/m·K]	*U-value* [$W/m^2\cdot K$]
Mineral wool (7% wood skeleton)	0.044	
Mineral wool	0.037	
Brick (1800 kg/m^3)	0.75	
Glazing, 1 layer, (4 mm)	1.66[1]	5.8
Glazing, 2 layer energy, (4-16-4)	0.033[1]	1.1
Glazing, 1+2, (4-30-4-16-4)	0.068[1]	0.9

Material	*Thermal conductivity, λ* [W/m·K]	*U-value* [W/m²·K]
Wood frame	0.13	
GRP frame (119 mm)	0.207[1]	1.42

[1] The thermal conductivity is calculated based on the total U-value and thickness excluding the surface heat transfer coefficients.

4.3 Thermal calculations

The thermal performance of the window-wall assembly was analysed as a 2D steady state problem investigated in HEAT2 ver. 7.1 (Blomberg 1996). The heat loss through the assembly and frame was calculated as the 2D coupling coefficient (L_{2D}) subtracting the 1D heat loss through the wall (Φ_{wall}) and window pane (Φ_{pane}) divided with the temperature difference (ΔT).

$$\Psi = (L_{2D} - (\Phi_{wall} + \Phi_{pane}))/\Delta T$$

For the box window the coupling coefficient was calculated as described in [EN ISO 10211:2007] for cases with more than two boundary temperatures.
For all three window-wall assemblies the grid was analysed changing the numbers of cells from n to 2n allowing a deviation of 1%.

4.4 Dew-Point Method

To evaluate the risk of moisture problems in the structures the dew-point method was applied. From the thermal calculations the temperatures were determined in critical points of the structure. These temperatures were compared to the dew-point temperature for the surrounding environment as described by Brandt [2009].

4.5 Daylight

The indoor environment was evaluated based on the amount of accessible daylight for the three windows. Velux Daylight Visualizer ver. 2.5.7 [Labayade *et al.* 2009, Velux 2010] was used for evaluation the daylight factor on a horizontal plane 0.85 m above the floor in a room of 3.8 x 5 m with two windows. A standard CIE overcast sky was used at the location for Denmark (latitude 55.4 and longitude 12.34). The internal surface reflectance was set to 0.9 for the walls, ceiling 0.9 and floor 0.35. The reference window was 1.6 x 1.1 m as the window with secondary glazing and box window. The windows were placed with a distance to each other on 0.8 m, 0.4 m away from the inner wall and 0.8 m above the floor. The light-transmittance for the reference window was 0.87 and 0.7 for the windows used for retrofitting.

5 RESULTS

5.1 Thermal

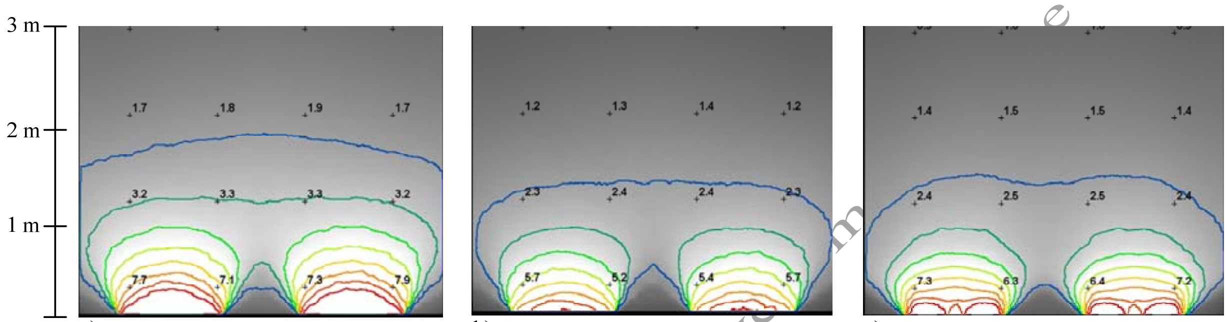
The thermal performance of the window-wall assembly is evaluated based on the total heat loss and the linear heat loss transmittance through the assembly and window frame. The existing window has a total heat loss of 55.3 W/m and the cold bridge is 0.41 W/(m·K). Adding a secondary energy glazing, 20 mm insulation in the cold bridge and 100 mm internal insulation the heat loss through the assembly is 0.37 W/(m·K) and the total heat loss is reduced to 17.4 W/m. The total heat loss for the box window is 12.8 W/m and the heat loss through the frame and assembly is 0.14 W/(m·K). Insulating the wall between the panes has only minor influence on the heat loss transmittance.

5.2 Dew-Point

The critical dew-point temperature in the structure is about 8°C regarding the internal environment. The reference window-wall assembly has condensation problems at the inside of the window pane.
For the two retrofit solutions condensation can occur in the wall-insulation interface and on the inside of the outside window. General the air cavity is a critical point if warm humid room air enters the cavity. In the cavity of solution 1 the joint between the frame, wall and insulation can be critical if the vapour barrier is not tight as the temperature is about 7.5°C. Solution 2 has lower temperatures at the surfaces and in structures because the new window is placed at the inside of the wall. The cavity surface temperatures are 3-5°C on the inside and outside frames in the cavity.

5.3 Daylight

The amount of daylight entering the room for the reference structure and the two retrofit solutions are shown in Fig. 3.



a) b) c)

Figure 3. The daylight factor for the three windows with a CIE overcast sky. a) is the existing window, b) is the window with secondary glazing and c) is the box window.

In the reference window the daylight factor is around 3.3% about 1.2 m in the room. At the same place the daylight factor is around 2.4% for the retrofitted solutions. Choosing a box window the amount of daylight entering the room is insignificant higher than using secondary glazing, which will decrease compared to the existing structure.

6 DISCUSSION AND CONCLUSION

Selection of new retrofit solutions is often chosen based on cost-efficiency according to energy savings. The choice of solution should instead be based on several different parameters e.g. durability, energy saving and indoor environment. Also non rational parameters should be considered as architecture and view out. An alternative approach to the cost-efficiency is the total economy considering the initial, operational and maintenance costs over the building lifetime. As the lifetime and economy is not included in the study the rational optimisation approach is attempted illustrated.

From the FMEA there are no larger differences in failure modes, consequences and causes between the box window and window with secondary glazing. The existing structure in the box window will be colder than for a window with secondary glazing as an effect of moving the "warm" building envelope to the inside of the room. As an effect of colder surface temperatures the cavity in the box window is more critical towards mould growth than for the window with secondary glazing. On the other hand the box window allows slightly more daylight to entering the room and a lower heat loss compared with the secondary glazing window; hence the heating and electricity consumption is decreased. In the total economy the maintenance costs is based on the founding in the FMEA and the operational costs are determined from the simulation of the energy savings and indoor environment. The retrofit solution is then chosen based on the total economy over the lifetime of building.

From the study of two window-wall assemblies a rational optimisation approach is illustrated about the total economy. The FMEA is used to investigate the durability of the component. Further the energy consumption and indoor environment is calculated as the heat loss, linear thermal transmittance and daylight for the two assemblies. In the total economy approach the initial costs, operational and maintenance costs needs to be included over the lifetime of the building.
The performance of the indoor environment influences the total energy consumption as overheating leads to cooling, reduced daylight increases electricity consumption and energy savings leads to less energy use for heating. In the rational approach every parameter needs to be included in the total economy and see the performance over the lifetime of the building.

Future work is to quantify the durability found in the FMEA using e.g. stochastic simulations. Further the determination of the operational and maintenance costs and the lifetime of the building are needed.

7 ACKNOWLEDGEMENT

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